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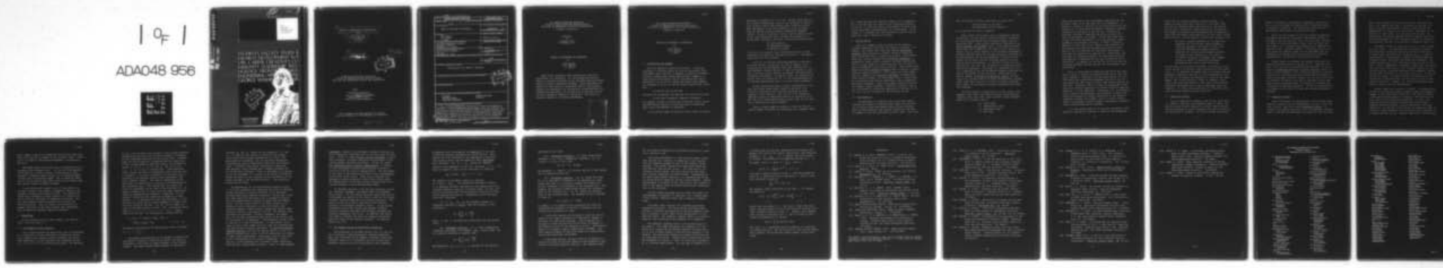

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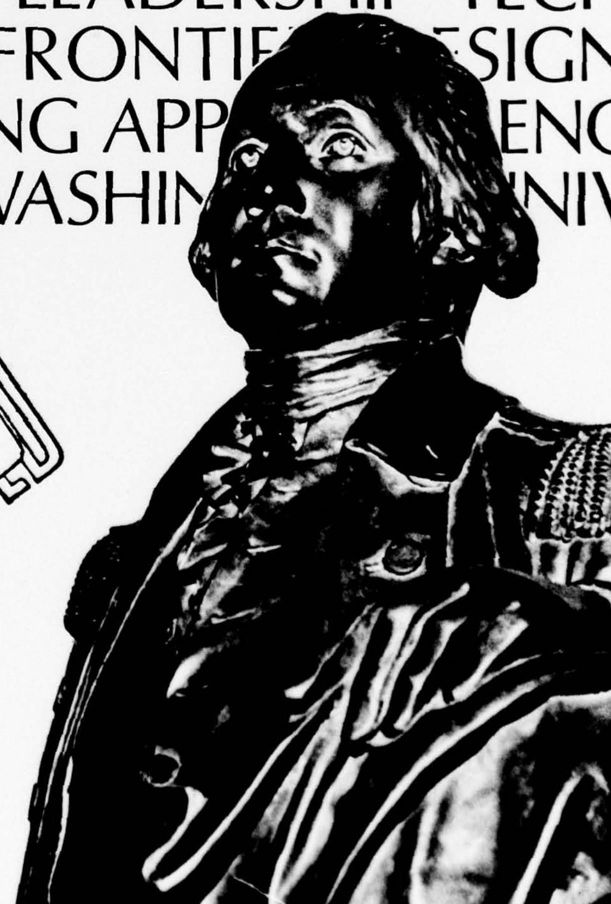

INSTITUTE FOR MANAGEMENT
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(6)

SURVEY OF APPROACHES TO READINESS,

by

(10) Zeev Barzily,
W. H. Marlow
S. Zacks

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About thirty unclassified references that feature naval logistics environments are considered. All ~~are unclassified and all~~ appear in the open literature or are available from the Defense Logistics Studies Information Exchange. Three approaches are identified--data analysis, theoretical models, and readiness indexes--and conclusions are presented as to possibilities for answering two questions: (a) can the unit do the job? and (b) how does "readiness" depend on "resources"? Four cases are treated in detail to illustrate methodology.

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SURVEY OF APPROACHES TO READINESS

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0. Introduction and Summary

There has doubtless always been interest in assessing "readiness" of military units to carry out particular tasks. Time frames have consisted of immediate instants or extended intervals, methods have ranged from personal judgments to sophisticated calculations, actual assessments have varied from merely "yes or no" to indexes and complicated probability statements, and so on, but the primary question has always been

(a) Can the unit do the job?

And given the assessment, the question for logistics has been

(b) How does "readiness" depend on resources?

For example, in Part I of [21] each of the four senior service representatives referred to these questions in addressing major issues and problems in logistics.

In the present paper we provide a brief survey of several approaches to answers for (a) or (b). We have found that we can, without disadvantage, restrict our attention to unclassified research reports that feature naval logistics environments and appear in the open literature, or are available from the Defense Logistics Studies Information Exchange (DLSIE). We start in Section 1 with a concise general review of the contribution and status of about 30 references; we divide these references into three convenient classifications:

(1) Data Analysis
(2) Theoretical Models
(3) Readiness Indexes

In Section 2 we present a more detailed discussion of four important cases which are reviewed in Section 1. Our general conclusions are the following.

First, by far the most promising approach to obtaining practical answers to questions (a) and (b) appears to be represented by the methodology study [20] conducted for the Navy Readiness Analysis System; it could be extended by inclusion of further cluster analysis techniques [28] and pattern recognition procedures. In specific cases, the generation of special data--as typified by [4]--or the straightforward use of existing authoritative data--as in [9]--seems worthwhile.

Second, theoretical models, such as represented by [11], [16], and others noted below, should be continued to be studied in connection with particular problems in which readiness can be involved. They are not to be regarded as immediate sources of operational answers to questions (a) or (b), but their study should produce results that will be helpful in devising practical procedures.

Third, we have found no evidence to indicate that hierarchical models involving the calculation of a readiness index of a system based on the readiness indexes of its components (as in [3] and [10]) are promising for answering questions (a) or (b). In the first place, requirements for data (especially functional representations) are overwhelming. In the second, it is doubtful that the hierarchies could be used as hoped for, even if data were available.

1. General Review

There are a number of ways in which we can classify different approaches that have been taken to readiness. For example, some efforts fall under the heading operational readiness where attention is mainly focused on operations that the military unit is required to perform. Such efforts often seek results somewhat like sufficient conditions in mathematics: given certain evidence, say from training exercises, a result might be a prediction that the unit will be able to accomplish a particular operation. Other efforts fall under the heading material readiness where attention is mainly focused on physical objects. Here results are often sought that are somewhat like necessary conditions in mathematics: given certain evidence, say from inspections, a result might be a prediction that the unit definitely cannot accomplish a particular operation. Other terms appear in the literature--for example, combat readiness, industrial readiness, and so on--but instead of classifying approaches in this way we use (1), (2), and (3) displayed in the preceding section.

1.1 Data Analysis

All approaches to readiness that we consider involve some kind of analysis of data but here under classification (1) we collect those that depend almost entirely thereon. Here the data evidently have logical connections with what is needed to carry out particular military tasks. The issues that distinguish different approaches are mainly two:

How pertinent are the data?
How defensible are the analyses?

Let us proceed to specific examples.

Early efforts on military worth--synonymously military essentiality--at the Logistics Research Project illustrate the first approach where special methods produce special applicable data. These efforts were mainly directed at the ships allowance list problem, which is the problem of determining the list of quantities of "repair parts" carried on board a ship in direct support of the installed "equipments." Readiness entered explicitly through coverage of question (a) by questionnaires for the determination of specific consequences on the ship's mission following need for the part when no spare was available. In the most serious case for question (b), the task--say the patrol of a submarine--would have to be terminated. The scheme for submarines given in [5] is modified in [4] for the Polaris weapons system and [6] applies the method to naval aviation. Particularly the Polaris scheme, of military essentiality classes, has had long use by the Navy both as a source of descriptors--highest worth, high worth, and so on--and for providing "readiness data" inputs for procedures and models connected with inventory problems.

The Navy produces various kinds of status reports (for example, Force Status and Identity Reports, Ready Material Condition data, and so on), many of which include readiness grades or "C-ratings" such as

C-1 Fully ready
C-2 Substantially ready
C-3 Marginally ready
C-4 Not ready

Grades are assigned by the individuals responsible for the military tasks, or in some cases for the "equipments," in question. Answers to question (a) are directly given in this fashion and, in cases where "resources" determine C-ratings, responses are also made to question (b). Reference [9] describes a method of analyzing and using such data for a fleet of destroyers, as follows. For one ship there are C-ratings for eleven subresources covering personnel, supply, equipment, and (average) training. A single C-rating is deduced for each ship using a "weakest link approach" and then average C-ratings are obtained for groups of ships. Measures are also obtained for individual subresources in ways that are responsive to question (b); specifically, the difficulty of improving readiness (by improving particular subresources) is addressed and the major problem areas are identified. In summary, we can say that in [9] the data are by design pertinent and the analyses are intentionally unsophisticated.

The U. S. Navy Board of Inspection and Survey has long been a source of data on the material condition of ships and their readiness. Reference [27] describes origins of a uniform analytical inspection methodology that was in use for a long period and [28] reports results from cluster analyses on such data. Reference [23] is a source of considerable information on different approaches to readiness based on physical condition. It also furnishes a substantial list of references. Data on repairs, modifications, and overhauls to ships similarly offer promise of helpful conclusions on the physical condition of ships; for example, [13] is an early study of effects of personnel, material supply, availability, obsolescence, and deterioration on readiness.

It is our opinion that by far the most substantial "data analysis" approach to readiness is given in the methodology study [20] for the Navy Readiness Analysis System. It reports on work during the second half of the 1960s when the Navy was committed under high priority to the development of such a system for, among other things, determining how changes in resources and environments can be expected to affect the performance and capabilities of Navy units, forces, and activities. In the words of its abstract, reference [20]

> Describes a method developed for systematically examining the relationships among personnel, training, equipment, and supply resource variables and destroyer performance measures. Equations for evaluating performance readiness of Atlantic Fleet destroyers at the end of refresher training are presented, and recommendations are made for improving performance measurement and resource data collection.

A broad range of statistical procedures are applied in [20], and in Section 2 we provide a short discussion of the methodology. It is important to comment that, in contrast with the approaches reported in Section 1.3, the methodology in [20] does not try to express the readiness of a ship by one index number, but instead provides a vector of readiness score factors which are uncorrelated. Each score factor provides additional information and is thus an important factor of readiness. We believe that anyone who is interested in pursuing readiness analysis should study [20].

1.2 Theoretical Models

In every approach to readiness that we have found there is a model of some kind, and somewhere there is theory, but here we collect efforts designed to provide models and analytical solutions to specific problems that may be related to the evaluation of readiness. We do not include theoretical models on inventory, maintenance, replacement, reliability, and so on, even though such matters affect important aspects of readiness evaluation. We include only models directly motivated by the problem of assessing readiness.

One of us has surveyed in [31] the problem of measuring and making statistical inference on operational readiness. The papers that are surveyed--[11], [22], and [30]--consider the model of a two-state Markov chain, "up" and "down" and the problems are to estimate the probability of readiness in particular ways. Another example is [29] which works with a time series of readiness grades for an individual ship as a continuous time Markov chain having stationary transition probabilities, and then deals with groups of ships.

Several papers on readiness and related areas were prepared at New York University during 1972-75. References [1], [14], [16], and [18] are concerned with measurement of readiness by a production function or utility function, similar to those used in economics. These functions constitute readiness data but they must describe level of performance (output) in terms of available resources (inputs) and, as such, valid ones are difficult to obtain, certainly as compared with any data that we have considered above. Reference [12] presents two techniques for measuring readiness. Effects of transportation are studied in [15] while [17] and [19] consider replacement problems.

1.3 Readiness Indexes

Under the present classification we collect studies that depend in essential ways on measurements, say on a scale from zero to unity, that can be called readiness indexes. In essence, such indexes represent values of functional relationships of the kind described above as production functions and, again, valid examples are difficult to find. The main idea here is to suppose that there is an index for each part of a large (typically hierarchical) complex system and that (by aggregation) the readiness of the system is determined as the value of a single index, or by at most a few of them. In other words, the present approach involves indexes that might perform analogously to "Gross National Product" in economics, "Intelligence Quotient" in psychology or education, and so on.

The METRI Project was sponsored by the U. S. Navy during the early 1960s. Its objective was to develop a system of using readiness indexes for measuring military essentiality of repair parts for (destroyer) allowance lists. A ship was represented as a hierarchical structure proceeding downward through missions, functional subsystems and components. The actual hierarchy was to be constructed using five basic structures--series, supplements, alternates, common, and collaterals--for which rules were given so that readiness indexes for subsystems could be calculated from those for components, indexes for missions from those for subsystems, and so on. In the end, effects of changes in inventory levels for parts were to be transmitted up the hierarchy. We review this project in more detail in Section 2. Reports [7], [8] and [24] provide some details, and [3] presents afterthoughts.

Project MARIS was a successor to METRI. It addressed the problem of relating the material support budget and budgetary changes to the operational capability of the Polaris weapons system and assessing impacts of changes in the logistics support system on the operational capability. It was a very large multi-echelon effort involving many data analyses, numerous theoretical models, several simulations, and great complexity. We include it here because an attempt was made to provide a single readiness index to measure the performance of a complex military system. Changes "down below," say in repair parts support, were to be transmitted "to the top" where they were to be read off as changes in the readiness index. Details are to be found in [10] and the methodology is discussed in Section 2.

The MAXCAP model of [25] and [26] is intended for use in preparing ships allowance lists. It fits well into approach (3) because it in effect involves a maximization of ships capability (readiness index) subject to a stipulated budget. It again uses a hierarchical model. But it should be noted that it was an internal Navy effort that was far smaller than the contract efforts in METRI and MARIS.

A motivating factor common to all of these efforts is the need to measure the effects of budgetary changes on the readiness of large-scale complex systems. The studies mentioned above attempted to index readiness as a function of factors that are influenced by budgetary constraints. However, the readiness indexes proposed do not attain the desired objective. They are usually very insensitive to changes that occur at the lower echelons and, furthermore, they are generally improper indexes of readiness.

2. Methodology

In this section we discuss four studies, two from Section 1.1 and two from 1.3.

2.1 Two Examples of Data Analysis

Let us again consider [9] where every ship is represented as a collection of eleven subresources (propulsion, navigation, communication, weapon systems, personnel, and so on). Each subresource is given a grade by the commanding officer: C-1, C-2, C-3, or C-4, as previously described. The question in [9] is how to analyze the vectors of eleven grades obtained periodically from each ship to obtain a pattern of readiness for the individual ships and for the entire fleet. A methodology for such an analysis is proposed based on conversion of the C-rating grades to numerical scores, by assigning the values 0 to C-1, 1 to C-4, and p_1 and p_2 ($0 < p_1 < p_2 < 1$) to C-2 and C-3, respectively. (These numerical scores reflect the state of unreadiness rather than the state of readiness.) The state of readiness of the whole ship is expressed as the minimal C-grade of the subresources (the worst readiness rating). The state of unreadiness of the whole fleet is expressed as an average of the unreadiness of the individual ships. This average does not reflect the extent of unreadiness in the sense of how difficult it is to improve readiness (or, in other words, how many subresources should be improved before readiness is improved). For the purpose of obtaining this additional information, a fleet measure, T, is constructed in the following manner. A subresource of a given ship is called <u>visible</u> if it agrees with the total rating of the ship. Let M_{ij} be the number of ships in the fleet having a visible ith subresource, being equal to C-j ($i = 1,\ldots,11$; $j = 1,\ldots,4$). A total fleet score for the ith subresource is defined then as

$$\begin{aligned} v_i &= M_{i1} \cdot 0 + M_{i2}p_1 + M_{i3}p_2 + M_{i4} \cdot 1 \\ &= p_1 M_{i2} + p_2 M_{i3} + M_{i4} \qquad ; \quad i = 1,\ldots,11 \,. \end{aligned}$$

The measure of difficulty for improving the state of unreadiness is $T = \sum_{i=1}^{11} v_i$.

The method discussed above is an attempt to quantify the qualitative C-ratings of ships and to measure the state of unreadiness of the fleet by proper averages of the obtained indexes. The quantification method depends on arbitrarily assigned p_1 and p_2 values for the categories C-2 and C-3. In addition, the indexes are based on the minimum rating value of the eleven subresources of a ship. This measurement of unreadiness may lose important information concerning the type of subresources that cause low readiness values. Different ships may be classified as having the same readiness level although their readiness problems may be substantially different. There is some doubt as to whether or not the assignment of C-ratings is an effective evaluation method and there also are concerns for the reliability of the grades provided by the concerned officers. These questions deserve special study.

The methodology for the Navy Readiness Analysis System in [20] gives procedures for expressing the level of readiness of Navy destroyers as certain functions of the Refresher Training Operational Readiness Inspection, briefly ORI, scores. The study involves 82 destroyers and is designed to analyze the relationship between resource variables and performance scores. The ORI scores relate to 29 areas of which 21 are related to mission functions, as anti-air warfare, anti-submarine warfare, surface warfare, command and control communications, mobility, and casualty control. The resource areas considered are personnel, training, equipment, and supply. Thus, the original performance data consist of 82 vectors (one for each ship) of 21 components. Each component (an ORI score) is provided by a team of inspectors. As anticipated, the 21 scores of the various subsections of a ship are correlated and some subsections are highly correlated. By applying <u>principal component analysis</u> (see [20] for special details or [2] as a general reference) the scores of the 21 subsections are reduced to eight linear combinations, with weights given by the eigenvectors corresponding to the largest eigenvalues. Factor analysis is then performed and a rotated 3-factor system provides the most interpretable solution. Factor 1, named <u>control</u>

procedures, involves six performance variables involving tactical information (resulting from the interpretation of radar data). Factor II, named casualty control procedures, involves four performance variables concerned with procedures of preventing damages and effecting repairs. Factor III, named anti-submarine warfare tactical communications, is defined by three performance variables which measure a series of activities with the chain of communications. The performance of each ship is then expressed by three values corresponding to the three factor scores. Ships can be clustered into homogeneous groups according to these three factor scores. The dimensionality of the data has been reduced from 21 correlated variables to three uncorrelated factors.

An important question is how the four resources: personnel, training, equipment, and supply affect the readiness factor scores. For this purpose multiple regression analysis is performed for each one of the factor scores on the various variables characterizing the four resource categories. This analysis shows the relative importance of the various resources on performance readiness factors. It can provide information on possible interactions between different resource categories (personnel and training, equipment and inventory management, and so on). In addition, the regression analysis provides the means for readiness estimation given the status of the resource variables. For specific details see [20].

2.2 Two Examples Based on Hierarchical Structures

The methodology of the METRI project [3], [7], and [8] was to construct a huge hierarchical structure modeling a Navy ship (destroyer) and to compose a readiness index from readiness values of its elementary units by certain rules. Readiness indexes are to be constructed for each component (elementary unit) according to the capability of its parts to function properly throughout the mission period. These indexes are to be functions of the reliability of the parts (the failure process) and the number of spare replacement parts available. Let $R_1,\dots,R_{n_i}$ denote the readiness indexes of the components in the ith subsystem $(i = 1,\dots,k)$; then the readiness index of that subsystem is a function

$$R_{S_i} = \phi_i(R_1,\dots,R_{n_i}),\ i = 1,\dots,k .$$

The readiness of the whole system is a function $R_T = f(R_{S_1},\dots,R_{S_k})$. The (apparently insolvable) problem is to determine suitable functions for the composition of the readiness indexes to serve as an overall index. For this purpose it was assumed that the hierarchical structure of a ship can be uniquely described as a combination of the following four basic structures:

(i) If $R_1,\dots,R_n$ are the readiness indexes of n components connected in series, then the readiness of the structure is

$$R_T = \left(\prod_{i=1}^{n} R_i^{\alpha_i}\right)^A ,$$

where α_i and A are empirical coefficients for the specific items.

(ii) Supplement structure. If n items independently supplement one another (for example, sonar, surface radar, and air radar for detection of enemies) then

$$R_T = \left(\sum_{i=1}^{n} K_i R_i^{\alpha_i}\right)^A$$

The parameters K_i, α_i $i = 1,\dots,n$ provide for the relative importance of the items.

(iii) Alternative structure. If a main system, whose readiness is R_1, has a standby unit (readiness R_2) to replace it in case it fails then

$$R_T = R_1 + (1 - R_1)KR_2 .$$

The parameter K expresses the relative ability of the standby unit to replace the main one.

(iv) Collateral structure. Let R_1 denote the readiness of a unit that is essential to the operation of a ship. Assume that there is a collateral element that affects the system's readiness in the presence of the essential unit. For example, the collateral element might provide for the maintenance of the essential unit. Let R_2 denote the readiness index of the collateral unit. The readiness of this structure is given by

$$R_T = R_1[K + (1 - K)R_2] .$$

In summary, it was supposed that in applying the rules for calculating the readiness of the basic structures, one can calculate the readiness of a ship.

A sensitivity analysis was proposed to show the rate of change in the overall readiness as a function of changes in the number of spare parts assigned. Such an analysis was designed to answer the question of the effect of changes in the inventory levels on the readiness of a ship. The proposed analysis is, however, vague in publications on METRI. The whole approach appears to have been found to be theoretically invalid and practically intractable.

As mentioned earlier, the main objective of MARIS was to relate the system of material support to the operational capability of the Fleet Ballistic Missiles. The readiness index was the expected proportion of operational missiles in a specified period of time.

The system considered is a three-echelon support system that contains four squadrons of submarines (first echelon) with one squadron assigned to each of four tenders (second echelon). The tenders reorder from stock points which procure material from outside sources. The stock points, the inventory control points, the repair facilities and industrial sources constitute the third echelon. Superimposed on the above three-echelon structure is a transportation system for moving material among the various system elements. Routine replenishment is provided by four cargo ships, one assigned to each of the tenders while occasional high priority transportation is also available.

The basic MARIS procedure aims to relate the budget for replenishment to readiness of submarines via: a budget model, a three-echelon simulation model, and a submarine readiness model.

The budget model simulates the estimated procurement expenditure for parts. The three-echelon simulation model provides a detailed representation of the Navy support system and it simulates actions taken and resulting effects of all possible events. The submarine readiness model is an analytic model for the evaluation of the readiness of a submarine.

The submarine readiness model is the essential part of the project. This model determines the readiness of a submarine as a function of the onboard inventory of spare parts. Let us give a simple example to show how the readiness is calculated. The spare parts treated are related to missiles and are replaceable on patrol. Suppose that a certain part has at the beginning of a patrol n units in stock and is installed in m different applications. For the sake of simplicity, it is assumed that the part has exponentially distributed independent life times at the various applications, with intensity parameters $\lambda_1,\ldots,\lambda_m$. If t denotes the first instant of stockout, the probability distribution function of t is the gamma $g(t|\bar{\lambda}, n)$ where $\bar{\lambda} = \sum_{j=1}^{m} \lambda_j$; that is,

$$g(t|\bar{\lambda}, n) = \frac{\bar{\lambda}}{\Gamma(n)} t^{n-1} e^{-\bar{\lambda}t} , \quad 0 \le t \le \infty .$$

Given that stockout occured at time t then the probability that all m units will still be operating y units of time after stockout is given by

$$\prod_{j=1}^{m} e^{-\lambda_j y} = \exp(-\bar{\lambda}y) .$$

The readiness index conditional on the time t of stockout was defined as

$$\begin{aligned} R_T(t) &= \frac{t}{T} + \frac{1}{T}\left[\int_0^{T-t} \exp(-\bar{\lambda}y)\,dy\right], & t \le T \\ &= 1 , & t > T . \end{aligned}$$

Notice that the product of T and $R_T(t)$ equals the conditional expected length of life of the system in a patrol given that a stockout occurred at time t . Finally, the readiness index related to this part with n units in stock is calculated by randomization, as follows:

$$\bar{R}_T(n) = \int_0^{\infty} R_T(t) g(t|\bar{\lambda}, n)\,dt .$$

Now $\bar{R}_T(n)$ is a reasonable index of readiness as a function of a particular part. But the question is, how can one combine these indexes? No satisfactory answer appears to have been given.

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